DESCRIPTION

MICROACTUATOR WITH DISPLACEMENT SENSING FUNCTION AND

DEFORMABLE MIRROR INCLUDING THE MICROACTUATOR

5 **TECHNICAL FIELD**

The present invention relates to a microactuator with a displacement sensing function and a deformable mirror including such a microactuator. The present invention also relates to various systems including such a microactuator.

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BACKGROUND ART

Various types of microactuators have been developed by microelectromechanical system (MEMS) technologies that use semiconductor processing. According to the MEMS technologies, 15 a lot of actuators, driver circuits and so on can be made at the same time. Thus, their applications have been broadened so as to make full use of their advantageous features. A deformable mirror, which is an arrangement of a huge number of micromirrors on a substrate, is one of those applications.

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The deformable mirror has found applications in compensating optical systems, displays, optical communications and other apparatuses to actively correct the wave front aberration of light.

5   The following two methods are known as conventional methods of controlling the magnitude of displacement of a deformable mirror.

One method is an open loop control in which the displacement of the mirror is controlled with drive voltages

10   applied in multiple stages (see R. W. Corrigan, D. T. Amm and C. S. Gudeman, "Grating Light Valve™ Technology for Projection Displays", presented at the International Display Workshop, Kobe Japan, Dec. 9, 1998, Paper Number LAD 5-1, for example). In this document, the deformable mirror is used as

15   a diffraction grating for controlling the amount of diffracted light with the magnitude of displacement of the mirror, which is subjected to an open loop control in multiple stages. This document also discloses the technique of correcting a variation in characteristic among a plurality of deformable

20   mirrors by empirically tracing the relationship between the

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drive voltage and the amount of diffracted light at several points in advance during a manufacturing process and by compiling a conversion table with those relationships interpolated.

5   The other method is a closed loop control using an external sensor. In a compensating optical system, for example, a control signal for a deformable mirror is generated based on an error signal that has been detected with a wavefront sensor, thereby performing a closed loop 10 control (see J. A. Perreault, T. G. Bifano et al., "Adaptive Optic Correction Using Microelectromechanical Deformable Mirrors", Optical Engineering, Vol. 41, No. 3, pp. 561-566 (March, 2002), for example).

    In the field of microsensors, the following technologies 15 are known. Some pressure sensors sense the deformation of a diaphragm under an external pressure as a variation in electrostatic capacitance (see S. B. Crary, W. G. Baer et al., "Digital Compensation of High-Performance Silicon Pressure Transducers", Sensors and Actuators, A21 to A23, pp. 70-72 20 (1990), for example). This document discloses a configuration

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in which relationships between the pressure and the sensor output are traced empirically in advance under multiple temperature conditions and in which a calibration polynomial, approximating these relationships, is stored in a memory.

5   There is also a force balanced pressure sensor, which makes another electrode produce electrostatic force to offset external pressure, performs a control so as to reduce the deformation of the diaphragm to substantially zero, and calculates the external pressure based on the magnitude of

10   that electrostatic force (see B. P. Gogoi, C. C. Wang and C. H. Mastrangelo, "Force Balanced Micromachined Pressure Sensors", IEEE Transactions on Electron Devices, Vol. 48, No. 8, pp. 1575-1584 (August 2001), for example).

      Some angular velocity sensors sense the magnitude of

15   displacement of a movable body due to the Coriolis force produced by an external angular velocity as a variation in electrostatic capacitance (see T. Juneau, A. P. Pisano and J. H. Smith, "Dual Axis Operation of a Micromachined Rate Gyroscope", Transducers '97, 1997 International Conference on

20   Solid-State Sensors and Actuators, Chicago, June 16-19, pp.

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883-886). This document discloses a configuration for correcting the drift of a zero point due to the initial positional error of a movable body.

These microactuators, however, have the following

5   drawbacks.

As for the microactuator for performing an open loop control by compiling a conversion table during the manufacturing process, it is troublesome to collect data to make the conversion table and the microactuator can cope with

10   a variation with time or according to the environment only within a certain limit. For example, to trace a relationship between the drive voltage and the amount of diffracted light, the amount of light needs to be measured pixel by pixel by actually irradiating the microactuator with external light.

15   Thus, a dedicated measuring device is needed and a lot of preparatory work, such as positioning the beam spot accurately, must be done. Consequently, it is very troublesome to collect the data required. Also, only the characteristic of the microactuator during the initial stage

20   of the manufacturing process can be evaluated and the

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magnitude of displacement of the moving section cannot be monitored once the microactuator has been built in an apparatus actually. For that reason, even if the characteristic of the actuator has changed due to either a variation with time or a variation according to the environment (e.g., the temperature variation), corrections cannot be made appropriately so as to cope with such a change.

The microactuator for performing a closed loop control using an external sensor such as a wavefront sensor requires, first of all, an expensive control system. To carry out a closed loop control with good stability, the number of sensing points of the wavefront sensor needs to be greater than the number of actuators included in the deformable mirror. In a Shack-Hartmann type wavefront sensor, for example, it is generally believed that the number of sensing points needs to be at least twice as large as that of actuators. Accordingly, a sensor with relatively high resolution is needed to carry out the closed loop control. In addition, positioning adjustment has to be done so as to associate each sensing point of the wavefront sensor with a

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driving point of the deformable mirror precisely enough. Furthermore, a relatively high-precision and large-scale controller is needed to perform computations (such as wavefront reconstitution) on a plurality of sensing signals

5   and generate control signals for respective driving points. Secondly, in that microactuator, a significant amount of light is lost by the wavefront sensor. The wavefront sensor senses the wavefront by using a portion of a bundle of rays, of which the wavefront should be corrected, thus leading to the loss of

10   the amount of light. If the number of sensing points on the wavefront is increased for the purpose of the closed loop control and if the sensor needs to guarantee prescribed sensitivity (i.e., S/N ratio) for each sensing point, then the wavefront sensor causes a significant loss in the amount of

15   light.

Furthermore, the microsensor such a pressure sensor or an angular velocity sensor has the following structural features and accompanying problems. First of all, the microsensor described in the document mentioned above senses

20   and controls the displacement of just one movable body.

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However, if a plurality of actuators needs to be driven at the same time as in a deformable mirror, for example, and if the microsensor performs the closed loop control on each of those actuators, then the circuit size becomes extremely big for that purpose. That is to say, the same number of sensing signal generators, amplifiers, A/D converters, controllers and other circuits as that of the actuators are needed for the purpose of displacement sensing. Particularly when there are a huge number of actuators, the circuit scale increases tremendously and the overall chip cost rises significantly.

A second problem is that no configuration for tracing the relationship between the drive signal and the displacement and self-calibrating it is disclosed in that document. Thus, it is difficult to apply the conventional technique to increasing the displacement precision of the actuators. Both the pressure sensor and the angular velocity sensor include a movable body, which is displaced under externally applied force, and a structure for converting the displacement of this movable body into a sensor output. However, the correspondence prestored in a memory is used

during this converting operation, and the correlation between

the displacement of the movable body and the output is fixed

except the zero point drift correction. The zero point drift

correction is done to correct the offset while the movable

5 body has not been displaced at all, and has essentially

nothing to do with the relationship between the drive signal

and the displacement. Accordingly, even if some mechanical

property has varied with time (e.g., a spring constant has

varied due to repetitive fatigue), that variation is not

10 correctible.

That is to say, a configuration for self-calibrating the

relationship between a drive signal for an actuator and the

displacement thereof while displacing the actuator is

disclosed in none of the documents cited above. Thus, it is

15 difficult in the prior art to compensate for the actuator

characteristic, which varies either with time or due to any

of various environmental factors, in a broad displacement

range.

In order to overcome the problems described above, an

20 object of the present invention is to provide a microactuator

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and a deformable mirror, which realize high-reliability positioning adjustment with a simple configuration and with a variation in characteristic with time or according to the environment corrected.

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DISCLOSURE OF INVENTION

A microactuator according to the present invention includes: a substrate; a moving element, which is supported on the substrate in a displaceable position; a driving section

10   for outputting a drive signal that causes displacement in the moving element; a converting section, which stores a correlation between the displacement of the moving element and the drive signal; a displacement sensing section for sensing the displacement of the moving element being supplied

15   with the drive signal; and a calibrating section for calibrating the correlation stored in the converting section with the drive signal and the output of the displacement sensing section.

In one preferred embodiment, the moving element includes

20   a fixed electrode, which is fixed on the substrate, and a

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movable electrode, which faces the fixed electrode, and the displacement sensing section senses the displacement of the moving element by a variation in electrostatic capacitance produced between the fixed electrode and the movable

5   electrode.

In another preferred embodiment, the driving section outputs, as the drive signal, a low-frequency signal, of which the frequency is approximately equal to, or lower than, the primary resonance frequency of the moving element. And

10   the displacement sensing section superposes, on the drive signal, a high-frequency signal, of which the frequency is equal to or higher than the primary resonance frequency of the moving element.

In another preferred embodiment, the driving section

15   outputs a substantial DC voltage as the drive signal.

In another preferred embodiment, the DC voltage output by the driving section as the drive signal has multiple stages. The displacement sensing section senses the displacement of the moving element in each of the multiple

20   stages. And the calibrating section approximates the DC

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voltage in each said stage and the output of the displacement sensing section with an approximation function of a predetermined form.

In another preferred embodiment, the driving section outputs, as the drive signal, a low-frequency signal having multiple stages of frequencies. The displacement sensing section senses the displacement of the moving element in which vibration has been produced. And the calibrating section calculates the amplitude response or phase response of the moving element by correlating the drive signal and the output of the displacement sensing section with each other.

In another preferred embodiment, the driving section outputs, as the drive signal, a low-frequency signal, of which the frequency is approximately equal to the primary resonance frequency of the moving element, in multiple stages. The displacement sensing section senses the displacement of the moving element in which vibration has been produced in each of the multiple stages. And the calibrating section extracts the primary resonance frequency of the moving element by correlating the drive signal and the

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output of the displacement sensing section with each other.

In another preferred embodiment, if the amplitude of the drive signal is defined high, the amplitude of the high-frequency signal, generated by the displacement sensing

5   section, is defined low.

In another preferred embodiment, the movable electrode of the moving element includes a first conductive portion and a second conductive portion, which are arranged substantially symmetrically to each other with respect to a predetermined

10 axis, and is supported so as to tilt freely around the axis. The fixed electrode includes a first electrode, which faces the first conductive portion of the movable electrode with a gap, and a second electrode, which faces the second conductive portion of the movable electrode with a gap. The

15 driving section supplies the drive signal to either between the first conductive portion and the first electrode or between the second conductive portion and the second electrode. The displacement sensing section applies a first high-frequency signal to the first electrode and a second

20 high-frequency signal, which has the same amplitude as, but

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an inverse phase to, the first high-frequency signal, to the second electrode, respectively, thereby detecting a voltage at a terminal where the first and second conductive portions are electrically connected together.

5   In another preferred embodiment, the converting section generates a voltage command value, which is associated with the displacement of the moving element. The driving section includes a D/A converter for outputting the drive signal that has been controlled in accordance with the voltage command

10   value. And the calibrating section calibrates a correlation between the voltage command value and the displacement of the moving element.

In another preferred embodiment, the D/A converter has a nonlinear characteristic and the larger the value of the

15   drive signal, the smaller the increase of the drive signal corresponding to that of the voltage command value.

In another preferred embodiment, the calibrating section approximates a correlation between the voltage command value and the displacement of the moving element with a linear

20   function.

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In another preferred embodiment, the calibrating section is activated when the microactuator is turned on.

In another preferred embodiment, the microactuator includes a temperature sensing section. The calibrating

5   section is activated when the temperature sensing section has sensed a temperature variation that is at least equal to a predetermined value.

In another preferred embodiment, the microactuator includes an abnormality detecting section for detecting an

10 abnormality in the moving element or the displacement sensing section when the output of the displacement sensing section is beyond a predefined range.

In another preferred embodiment, if the abnormality detecting section has detected any abnormality, the

15 calibrating section is prohibited from updating the correlation.

Another microactuator according to the present invention includes: a substrate; a plurality of moving elements, which are supported on the substrate in a displaceable position; a

20 driving section for outputting a drive signal that causes

displacement in the moving elements; a displacement sensing section for sensing the displacement of the moving elements; and a switching section for selectively connecting the driving section and/or the displacement sensing section to

5   one of the moving elements after another.

In one preferred embodiment, the switching section senses the displacement of each said moving element while switching time-sequentially objects of the displacement sensing by the displacement sensing section.

10   In another preferred embodiment, the microactuator includes a closed loop control section for performing a closed loop control on the output of the driving section with the output of the displacement sensing section.

In another preferred embodiment, the microactuator

15   further includes an open loop control section for performing an open loop control on the output of the driving section and controls the moving elements by switching the closed loop control section and the open loop control section time-sequentially.

20   In another preferred embodiment, the open loop control

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section includes a holding section for holding the output of the driving section that is under the control of the closed loop control section.

In another preferred embodiment, the moving elements are provided so as to store charges in accordance with the drive signal. The switching section switches the moving elements between a first state, in which the moving elements are connected to the closed loop control section, and a second state, in which the moving elements have impedance that is high enough to store the charges.

In another preferred embodiment, the microactuator includes a counter for calculating a value representing the amount of time in which each said moving element is connected to the closed loop control section and a convergence detecting section for detecting the convergence of the closed loop control. Unless the convergence detecting section detects the convergence even when the output of the counter exceeds a predetermined upper limit, the switching section disconnects the moving element from the closed loop control section.

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In another preferred embodiment, the value representing the amount of time in which the moving element is connected to the closed loop control section is the number of times that the closed loop control section performs its loop

5   repeatedly.

In another preferred embodiment, if the output of the counter is less than the upper limit when the switching section switches the connection of the closed loop control section to the next moving element upon the detection of the

10   convergence by the convergence detecting section, the upper limit of the next moving element is changed according to the output of the counter.

In another preferred embodiment, the switching section connects at least two of the moving elements to the

15   displacement sensing section simultaneously.

In another preferred embodiment, a bias voltage, of which the magnitude is approximately equal to or greater than the amplitude of the high-frequency signal, is applied to both the fixed electrode and the movable electrode.

20   Still another microactuator according to the present

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invention includes: a substrate; a moving element, which is supported on the substrate in a displaceable position; a driving section for outputting a drive signal that causes displacement in the moving element; a displacement sensing

5   section for sensing the displacement of the moving element; a switching section, which is provided for an interconnection line that connects the driving section and/or the displacement sensing section to the moving element so as to switch the interconnection line from a connected state into a

10 disconnected state, or vice versa; and a calibrating section for correcting a first output of the displacement sensing section, which is obtained with the interconnection line connected, with a second output of the displacement sensing section, which is obtained with the interconnection line

15 disconnected.

Yet another microactuator according to the present invention includes: a substrate; a moving element, which is supported on the substrate in a displaceable position; a driving section for outputting a drive signal that causes

20 displacement in the moving element; and a displacement

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sensing section for sensing the displacement of the moving

element being supplied with the drive signal. The moving

element includes a fixed electrode, which is fixed on the

substrate, and a movable electrode, which faces the fixed

5   electrode. The movable electrode includes a first conductive

portion and a second conductive portion, which are arranged

substantially symmetrically to each other with respect to a

predetermined axis, and is supported so as to tilt freely

around the axis. The fixed electrode includes a first

10   electrode, which faces the first conductive portion of the

movable electrode with a gap, and a second electrode, which

faces the second conductive portion of the movable electrode

with a gap. The driving section generates a first drive

signal to be applied to the first electrode and a second

15   drive signal, which has a different magnitude from that of

the first drive signal and which is applied to the second

electrode. The displacement sensing section includes: a

high-frequency signal generating section for outputting a

high-frequency signal, of which the frequency is equal to or

20   higher than a primary resonance frequency of the moving

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element; a first load impedance component, which is connected to the first electrode at a first terminal; a second load impedance component, which is connected to the second electrode at a second terminal; and a high frequency

5   detecting section, which is connected to the first and second terminals.   The   first   drive   signal   on   which   the   high-frequency signal is superposed is applied to the other terminal of the first load impedance component that is opposite to the first terminal.   The second drive signal on

10   which the high-frequency signal is superposed is applied to the other terminal of the second load impedance component that is opposite to the second terminal.   The high frequency detecting section compares the phases and/or the amplitudes of the high-frequency signal between the first and second

15   terminals, thereby sensing the displacement of the moving element.

A deformable mirror according to the present invention includes one of the microactuators described above.   A light reflective region is defined in at least a portion of the

20   moving element.

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A system according to the present invention includes one of the microactuators described above.

A driving method according to the present invention is a method of driving a microactuator including a moving element. The method includes the steps of: outputting a drive signal that causes displacement in the moving element; storing a correlation between the displacement of the moving element and the drive signal; sensing the displacement of the moving element being supplied with the drive signal; and calibrating the correlation with the drive signal and the output of the displacement sensing section.

BRIEF DESCRIPTION OF DRAWINGS

FIG. 1 illustrates the schematic configuration of a microactuator according to a first preferred embodiment of the present invention.

FIG. 2 shows the schematic configuration of a driver circuit for the microactuator of the first preferred embodiment of the present invention.

FIG. 3 is a flowchart showing a calibrating operation

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routine according to the first preferred embodiment of the present invention.

FIG. **4** illustrates the schematic configuration of a microactuator according to a second preferred embodiment of

5   the present invention.

FIG. **5** is a flowchart showing an intermittent closed loop control routine according to the second preferred embodiment of the present invention.

FIG. **6** illustrates the schematic configuration of a

10   microactuator according to a third preferred embodiment of the present invention.

FIG. **7** is a flowchart showing an intermittent closed loop control routine according to the third preferred embodiment of the present invention.

15   FIG. **8** is an exploded perspective view of a microactuator according to a fourth preferred embodiment of the present invention.

FIG. **9** shows the schematic configuration of a driver circuit **100a** according to the fourth preferred embodiment of

20   the present invention.

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FIG. **10** is a flowchart showing a calibrating operation routine according to the fourth preferred embodiment of the present invention.

FIGS. **11(a)** and **11(b)** are graphs showing correlations between the voltage command value **D** and displacement of a moving element.

FIG. **12** illustrates the schematic configuration of a microactuator according to a fifth preferred embodiment of the present invention.

FIG. **13** illustrates the schematic configuration of a microactuator according to a sixth preferred embodiment of the present invention.

FIG. **14(a)** illustrates the schematic configuration of a nonlinear D/A converter **176** according to the sixth preferred embodiment of the present invention, and FIG. **14(b)** is a graph showing correlations between the voltage command value **D** and the displacement **Z** in its calibrating section **178**.

BEST MODE FOR CARRYING OUT THE INVENTION

Hereinafter, preferred embodiments of the present

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invention will be described with reference to the accompanying drawings.

EMBODIMENT 1

First, a first preferred embodiment of a microactuator according to the present invention will be described with reference to FIGS. 1 through 3. The microactuator of this preferred embodiment is an electrostatic actuator that performs a tilting operation. Such a microactuator may be fabricated by semiconductor device processing technologies, for example. The microactuator of this preferred embodiment is applicable to a deformable mirror for controlling the reflection direction of light in multiple stages.

First, referring to FIG. 1, illustrated is the schematic configuration of a microactuator according to this preferred embodiment. As shown in FIG. 1, a driver circuit 2 is provided on a substrate 1, which may be a silicon wafer, and is covered with an insulating layer 3 with a thickness of at least 30 μ m. A moving section 4 is formed of a number n (which is an integer equal to or greater than two) of moving

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elements **A1** through **An** on the insulating layer **3**. In the

moving section **4**, the respective moving elements **A1** through **An**

have the same configuration. Thus, an ith (where i is an

integer equal to or greater than one) moving element **Ai** will

5   be described as an example. The moving element **Ai** includes

two fixed electrodes E_{Li} and E_{Ri}, a movable electrode **Yi**

provided so as to face these fixed electrodes E_{Li} and E_{Ri}, and

a pair of conductive posts **Pi** that supports this movable

electrode **Yi** in a tilting position.

10   The moving element **Ai** has a horizontally symmetrical

shape with respect to the posts **Pi**. The movable electrode **Yi**

includes a first conductive portion Y_{Li} and a second

conductive portion Y_{Ri}. The first conductive portion Y_{Li} faces

the first electrode E_{Li} with a gap and the second conductive

15   portion Y_{Ri} faces the second electrode E_{Ri} with a gap. The

upper surface of the movable electrode **Yi** functions as a

reflective mirror for reflecting incoming light.

When a potential difference is created between the first

electrode E_{Li} and the movable electrode **Yi** or between the

20   second electrode E_{Ri} and the movable electrode **Yi**, the movable

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electrode Y_i tilts either counterclockwise or clockwise due to electrostatic force. As a result, the direction of the light reflected by the upper surface of the movable electrode Y_i changes. By regulating the magnitude of the potential difference, the tilt angle of the movable electrode Y_i can be controlled.

Suppose a capacitor formed by the first electrode E_{Li} and the first conductive portion Y_{Li} of the movable electrode Y_i has a capacitance C_{Li} and a capacitor formed by the second electrode E_{Ri} and the second conductive portion Y_{Ri} of the movable electrode Y_i has a capacitance C_{Ri}. In that case, in the initial state in which the movable electrode Y_i is in horizontal position, $C_{Li} = C_{Ri}$ is substantially satisfied.

The capacitances C_{Li} and C_{Ri} increase or decrease in mutually opposite directions according to the tilt and displacement of the movable electrode Y_i. In this preferred embodiment, the displacement of the movable electrode Y_i is sensed by detecting the variations in the capacitances C_{Li} and C_{Ri}.

Terminals T_{Li}, T_{Ri} and T_{Pi} are connected to the fixed

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electrodes E_{L1} and E_{R1} and posts $P1$, respectively. These terminals are connected to the driver circuit 2 as via metals extending through the insulating layer 3.

Next, the driver circuit 2 will be described in detail with reference to FIG. 2, which shows the schematic configuration of a driver circuit for a microactuator according to this preferred embodiment.

The driver circuit 2 includes an overall control section 5, a displacement sensing section 6 for sensing the displacement of each moving element $A1$ and a switching section 7 for selecting a moving element as an object of displacement sensing by the displacement sensing section 6.

The control section 5 includes an I/F section 10, a target displacement setting section 11, a converting section 12, a voltage command section 13, a displacement sensing control section 14, a calibrating section 15, a first drive voltage generating section 20 and a second drive voltage generating section 22. In this preferred embodiment, the voltage command section 13 and the first and second drive voltage generating sections 20 and 22 together form a "driving

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section".

The I/F section **10** exchanges commands and data with an external control-related unit.

The target displacement setting section **11** sets the

5 respective target displacements of the moving elements **A1** through **An** in accordance with the output of the I/F section **10**.

The converting section **12** converts the respective target displacements of the moving elements **A1** through **An** into target

10 data associated with the drive voltages. In the converting section **12**, correlations between the drive voltages and displacements of the respective moving elements **A1** through **An** are stored as a conversion table. The variation in characteristic among the respective moving elements **A1** through

15 **An** is corrected here.

In controlling the respective moving elements **A1** through **An**, the voltage command section **13** outputs voltage command values $D(V_{L1})$ through $D(V_{Ln})$ and $D(V_{R1})$ through $D(V_{Rn})$ for displacing the moving elements **A1** through **An** in accordance

20 with the output of the converting section **12**. The voltage

command values $D(V_{L1})$ through $D(V_{Ln})$ and $D(V_{R1})$ through $D(V_{Rn})$ are associated with the drive voltages V_{L1} through V_{Ln} and V_{R1} through V_{Rn} to be applied to the terminals T_{L1} through T_{Ln} and T_{R1} through T_{Rn} of the fixed electrodes. On the other hand, in

5   sensing the displacement of the moving element $A1$, the voltage command section 13 changes the voltage command values $D(V_L)$ and $D(V_R)$ such that the difference V_L-V_R between the DC components V_L and V_R of the drive voltages to be applied to the fixed electrode terminals T_{Li} and T_{Ri} is changed at a

10   predetermined timing. In this preferred embodiment, one of V_L and V_R is set equal to 0 V and the other is increased from 0 V step by step on a predetermined voltage basis as an example. The control values of V_L and V_R generated by the voltage command section 13 and their timings of change are controlled

15   in accordance with the output of the displacement sensing control section 14.

The displacement sensing control section 14 instructs the voltage command section 13 to change the voltage command values $D(V_L)$ and $D(V_R)$. Also, the displacement sensing

20   control section 14 turns ON the transistor 26 of the

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displacement sensing section **6** and keeps it ON for a

predetermined period of time, thereby removing the offset of

the sensing signal **Vout**. In this manner, the variation in the

sensing signal **Vout** due to the change of the voltage command

5   values $D(V_L)$ and $D(V_R)$ can be canceled.

The calibrating section **15** receives the voltage command

values $D(V_L)$ and $D(V_R)$ from the voltage command section **13** and

the displacement sensed for the moving element **Ai** from the

displacement sensing section **6**, respectively, thereby

10   compiling the correlations between the voltage command values

$D(V_L)$ and $D(V_R)$ and the displacements. These correlations are

fitted with an approximation curve of a predetermined form

such that the measuring errors are eliminated. Then, the

resultant interpolated correlations are stored in the

15   conversion table of the converting section **12**.

In accordance with the voltage command value $D(V_L)$

supplied from the voltage command section **13**, the first drive

voltage generating section **20** generates a DC voltage V_L.

Likewise, in accordance with the voltage command value $D(V_R)$

20   supplied from the voltage command section **13**, the second drive

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voltage generating section 22 generates a DC voltage V_R.

The displacement sensing section 6 includes a first high-frequency signal generating section 21, a second high-frequency signal generating section 23, an operational

5   amplifier 24, a capacitor 25, the transistor 26, an amplifier 27 and an A/D converter 28.

The first high-frequency signal generator 21 generates an AC voltage with an amplitude V_A and a frequency f. The frequency f may be a predetermined value falling within the

10   range of 100 kHz to 1 MHz and is supposed to be higher than the primary resonance frequency fo (of 1 kHz to 10 kHz) of the moving element A1. The first drive voltage generating section 20 and the first high-frequency signal generating section 21 are connected in series together. And a first output voltage

15    $V_L + V_A \sin(2\pi ft)$ is obtained as the sum of their outputs.

The second high-frequency signal generating section 23 generates an AC voltage, which has the same amplitude V_A and the same frequency f as those of the AC voltage generated by the first high-frequency signal generating section 21 but the

20   phase of which is different by 180 degrees from that of the AC

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voltage generated by the first high-frequency signal generating section **21**. The second drive voltage generating section **22** and the second high-frequency signal generating section **23** are connected in series together. And a second

5   output voltage $V_R - V_A \sin(2\pi ft)$ is obtained as the sum of their outputs.

If connection to the moving element **A1** has been selected by the switching section **7**, then the first and second output voltages $V_L + V_A \sin(2\pi ft)$ and $V_R - V_A \sin(2\pi ft)$ are input

10   through the terminals T_{Li} and T_{Ri}, respectively, and the output through the terminal T_{Pi} is input to the operational amplifier **24**. The output **Vout** of a circuit consisting of the operational amplifier **24** and the capacitor **25** with capacitance **Cf** is given by the following Equation (1), of which the second term of the

15   right side represents an offset caused by the variations ΔV_L and ΔV_R of the drive voltages V_L and V_R. Accordingly, if this offset is eliminated by turning the MOS transistor **26** ON before the detection as described above, a signal for detecting the variation C_{Ri}-C_{Li} in electrostatic capacitance

20   can be obtained accurately.

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$$\text{Vout} = ((C_{Ri} - C_{Li})/Cf) \cdot V_A \sin(2\pi ft) + (C_{Ri}\triangle V_R + C_{Li}\triangle V_L)/Cf \qquad (1)$$

The output **Vout** is amplified by the amplifier **27**, converted into digital data by the A/D converter **28** and then output to the calibrating section **15**.

5   The switching section **7** switches each of the moving elements **A1** through **An** from a drive mode in which the moving element is driven and controlled into a sensing mode in which its displacement is sensed, or vice versa. In FIG. **2**, the moving element **Ai** has been turned to the sensing mode, is

10   connected to the displacement sensing section **6** as described above, and its response characteristic is being checked out. On the other hand, in FIG. **2**, the moving element **A$_{i+1}$** has been turned to the drive mode, in which voltages **V$_{Li+1}$** and **V$_{Ri+1}$** as instructed by the voltage command section **13** are applied to

15   the fixed electrode terminals **T$_{Li+1}$** and **T$_{Ri+1}$**, respectively, and the movable electrode terminal **T$_{Pi+1}$** is connected to the ground potential, whereby the moving element **A$_{i+1}$** is driven to the target position.

Hereinafter, it will be described with reference to FIG.

20   **3** how the microactuator with such a configuration operates.

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FIG. 3 is a flowchart showing the calibrating operation routine to be carried out by the microactuator of this preferred embodiment.

When the system is started, or when the temperature sensor (not shown) has sensed a temperature variation, of which the magnitude is equal to or greater than a predetermined value, or when the built-in timer has counted an operating time, of which the length is equal to or greater than a prescribed value, since the conversion data was updated last time, the microactuator of this preferred embodiment updates the conversion table of the moving elements **A1** through **An** as stored in the converting section **12**.

First, by setting $i = 1$ (in Step **30**), the first moving element **A1** is selected as the moving element **Ai** of which the displacement should be sensed. The switching section **7** connects the moving element **Ai** to the displacement sensing section **6** (in Step **31**). In this case, all moving elements but the moving element **Ai** are disconnected from the displacement sensing section **6**.

During the displacement sensing, the voltage command

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values $D(V_L)$ and $D(V_R)$ output by the voltage command section 13 are changed and the output voltages V_L and V_R of the first and second drive voltage generating sections 20 are applied in multiple stages, thereby sensing the displacement of the moving element A1 in each of those stages. More specifically, first, V_R is set equal to 0 V (in Step 32) and V_L is gradually increased from 0 V to the maximum voltage **Vmax**, thereby measuring the displacement of the moving element A1 at each of those voltages.

The displacement data thus obtained is stored, along with the respective V_L values, in the calibrating section 15 (in Step 33). Next, V_L is set equal to 0 V (in Step 34) and V_R is gradually increased from 0 V to the maximum voltage **Vmax**, thereby measuring the displacement of the moving element A1 at each of those voltages. The displacement data thus obtained is stored, along with the respective V_R values, in the calibrating section 15 (in Step 35). When the measurement is finished, the calibrating section 15 fits the relationship between the voltage difference V_L-V_R and the displacement data to a predetermined approximation function, thereby calculating

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the coefficients of respective terms of the approximation function and the correlated values thereof (in Step 36).

For the coefficients and correlated values of the respective terms of this approximation function, ranges, in which every value is regarded as a normal value, are defined in advance. And it is determined whether or not these values obtained fall within these normal ranges (in Step 37). If any value falls out of its normal range, then it is determined that there is an error in the result of measurement (in Step 38). The contents of the error processing change according to the coefficients and correlated values. Specifically, if any value falls out of its normal range just slightly, then measurement is carried out again. For example, if the moving element is hardly displaced irrespective of the voltage value of V_L or V_R, then the moving element or the displacement sensing section 6 is regarded as out of order, the error is identified, and the update of the conversion table is prohibited.

On the other hand, if every value falls within its normal range, then the results of measurement are regarded as valid,

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the conversion table is updated (in Step **39**) and the next moving element starts to be measured (in Step **40**). When the measurement of the nth moving element **An** is finished, the conversion table compiling routine ends.

5   When the conversion table has been compiled, the microactuator starts to perform a control operation by using that table. The switching section **7** turns all of the moving elements **A1** through **An** to the drive mode in which the moving elements are driven and controlled.

10   In this preferred embodiment, every moving element performs an open loop control. When the target displacement of each of the moving elements **A1** through **An** is set by the target displacement setting section **11**, the target displacement is converted into target data associated with the

15 drive voltage by the converting section **12**. Being supplied with the drive voltage instructed by the voltage command section **13**, each of the moving elements **A1** through **An** is controlled to its desired position.

As described above, the microactuator of this preferred

20 embodiment includes a configuration for sensing the magnitude

of displacement, caused by its own driving force, by itself. Accordingly, no external displacement measuring device is needed, no troublesome setting-related work (such as alignment) needs to be done, and a conversion table for

5 correcting the variation in characteristic among individual moving elements can be compiled very easily.

In addition, the microactuator can make the measurement while built in a system, and therefore, can cope with any variation in the characteristic of a moving element due to

10 either a variation in time or an environmental variation such as a temperature variation.

Furthermore, the microactuator senses the displacement while making the switching section 7 selectively and cyclically connect the single displacement sensing section 6

15 to one moving element after another. Accordingly, even an actuator with a lot of moving elements can have a significantly reduced number of sensing signal generators, amplifiers and A/D converters for the purpose of displacement sensing. As a result, the circuit size can be reduced and the

20 chip cost can be cut down.

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In the preferred embodiment described above, the drive voltage generating section **20** and high-frequency signal generating section **21** are separately provided and connected together. Alternatively, these generating sections **20** and **21**

5 may be implemented as a single D/A converter such that the output voltage $V_L + V_A \sin(2\pi ft)$ is obtained by modulating the output control signal of the voltage command section **13** at the frequency **f**. Also, the waveform of the AC voltage does not have to be a sine wave but may also be a rectangular wave as

10 well. The same statement applies to the drive voltage generating section **22** and high-frequency signal generating section **23**, too. Then, the majority of the signal generating circuit for displacement sensing can be used in common with the circuit for drive and control. As a result, the overall

15 circuit configuration can be simplified.

Also, in the voltage command section **13** described above, only the DC voltage components V_L and V_R are variable. Optionally, the amplitude V_A of the AC voltage component may also be variable, too. In particular, if the amplitude V_A is

20 increased when the potential difference $V_L - V_R$ has a small

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absolute value and decreased when the potential difference V_L $-$ V_R has a large absolute value, then the following two effects are achieved. Firstly, the responsivity can be increased while the effects of the AC voltage component on the

5   displacement of the moving element is minimized. When the potential difference V_L $-$ V_R has a small absolute value, the displacement of the moving element **A1** is small and the variation C_{Li} $-$ C_{Ri} in electrostatic capacitance is also small. Thus, the sensing signal **Vout** has a small amplitude and it is

10   difficult to achieve a high SNR. Meanwhile, the attraction produced by the AC voltage component on the fixed electrode E_{Li} side of the moving element **A1** is almost in balance with that produced by the AC voltage component on the fixed electrode E_{Ri} side thereof. As a result, these attractions

15   cancel each other and hardly affect the displacement of the moving element if ever. The opposite characteristics are exhibited if the potential difference V_L $-$ V_R has a large absolute value. For that reason, if the amplitude V_A is increased when the potential difference V_L $-$ V_R has a small

20   absolute value and decreased when the potential difference V_L

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$-V_R$ has a large absolute value, then the responsivity can be increased while the effects of the AC voltage component on the displacement of the moving element is minimized. Secondly, the moving element can have a broadened measurable displacement range with respect to the same supply voltage. The measurable displacement range of the moving element is defined by the DC voltage setting range and is obtained by removing the AC voltage component from the overall voltage. By decreasing the amplitude V_A when the drive voltage V_L or V_R has a large absolute value, the moving element can have a broadened measurable displacement range with respect to the same supply voltage.

In the preferred embodiment described above, the displacement sensing section 6 has just a single channel. Alternatively, the displacement sensing section 6 may have a plurality of channels, the moving elements **A1** through **An** may be divided into a plurality of blocks, and each channel of the displacement sensing section 6 may perform the cyclic check on its associated block.

Also, in the preferred embodiment described above, the

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moving elements are connected to the displacement sensing

section **6** one by one. However, a plurality of moving elements

may be connected to the single displacement sensing section **6**

at the same time. In that case, the variations of the

5   respective moving elements are averaged and the variation in

overall characteristic can be sensed with good accuracy. If

every moving element changes its characteristic according to a

substantially uniform pattern in response to an environmental

variation such as a temperature variation, then the overall

10   correction data obtained in this manner may be added to the

conversion data of each moving element.

Furthermore, in the preferred embodiment described above,

the drive signal is supposed to be a DC signal. However, the

drive signal does not have to be a DC signal. Alternatively,

15   if a drive signal having a low frequency that is equal to or

lower than the primary resonance frequency of a moving element

is supplied as the drive signal that produces a desired

displacement in the moving element and if the amplitude and

phase of the moving element are measured by the displacement

20   sensing section **6**, then the response characteristic of the

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moving element can be estimated, too. Also, if the resonance

point is searched for by shifting the frequency of the drive

signal in the vicinity of the primary resonance frequency of

the moving element, then the resonance frequency of the moving

5   element itself can be measured and the response characteristic

of the moving element can also be estimated accurately, too.

The calibrating section **15** can calculate the voltage-

displacement curve of the moving element based on these

response characteristics and can use it by storing it in the

10   converting section **12**. As to the primary resonance frequency

fo of the moving element and the tilt-related spring constant

k, the variation in the primary resonance frequency **fo** can be

detected and the static relationship between the drive voltage

and the displacement can be calibrated by utilizing the

15   relationship that fo is proportional to the square root of k.

Furthermore, in the preferred embodiment described above,

the moving element is supposed to be an electrostatic moving

element and the displacement sensing section **6** adopts an

electrostatic capacitance detection method in sensing the

20   displacement. However, the present invention is in no way

limited to this specific preferred embodiment. Alternatively, a piezoelectric element may be used as the moving element and the displacement may be sensed by utilizing those piezoelectric effects.

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EMBODIMENT 2

Hereinafter, a second preferred embodiment of a microactuator according to the present invention will be described with reference to FIGS. **4** and **5**. FIG. **4** illustrates

10   the schematic configuration of a microactuator according to this preferred embodiment.

In the microactuator of this preferred embodiment, each of the moving section **4**, displacement sensing section **6**, switching section **7**, I/F section **10**, target displacement

15   setting section **11** and displacement sensing control section **14** has the same configuration as the counterpart as already described for the first preferred embodiment. The difference between this and first preferred embodiments lies in the configuration of the control section **50**. In this preferred

20   embodiment, the control section **50** performs an intermittent

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closed loop control on the moving elements **A1** through **An** by using the output of the displacement sensing section **6**.

The control section **50** includes a voltage command section **51**, which includes a servo control section **52** and a voltage value holding section **53**.

The servo control section **52** includes a PID controller, which receives the difference between the target displacement setting section **11** and the displacement sensing section **6** as an error signal ε and realizes a desired control characteristic. By providing the command values of the voltages V_L and V_R as its control outputs, the servo control section **52** carries out a closed loop control on a selected moving element **Ai**. Also, when the value of the error signal ε and its time differential value decrease to predetermined values or less, the servo control section **52** judges that the control described above has converged. Then, the control section **52** terminates the closed loop control on the moving element **Ai**, switches it into an open loop control, and performs a closed loop control on the next moving element **Ai+1**. More specifically, on detecting the convergence of the

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control, the servo control section 52 outputs the command

values of the voltages V_L and V_R at that point in time to the

voltage value holding section 53. In response, the voltage

value holding section 53 keeps outputting the command values

5   of the voltages V_L and V_R as command values V_{Li} and V_{Ri} for the

moving element A_i until the servo control section 52 inputs

new command values about the moving element A_i again. The

switching section 7 switches the connection of the moving

element A_i from the displacement sensing section 6 to the

10   voltage value holding section 53 and also switches the

connection of the moving element A_{i+1} from the voltage value

holding section 53 to the displacement sensing section 6.

Hereinafter, it will be described with reference to FIG.

5 how the microactuator having such a configuration operates.

15   FIG. 5 is a flowchart showing an intermittent closed loop

control routine to be done by the microactuator of this

preferred embodiment.

First, by setting i = 1 (in Step 60), the first moving

element A_1 is selected as a moving element A_i to be subjected

20   to the closed loop control. The switching section 7 connects

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the moving element **A1** to the displacement sensing section **6** (in Step **61**).   At this point in time, all of the moving elements but the moving element **A1** are connected to the voltage value holding section **53** and an open loop control is being carried out based on its output value.

As the initial control voltage values V_L and V_R of the moving element **A1**, the V_{Li} and V_{Ri} values that were held in the voltage value holding section **53** last time are used (in Step **62**).   The displacement sensing section **6** senses the displacement of the moving element **A1** and the servo control section **52** performs a closed loop control such that the magnitude of the displacement sensed matches the target displacement output by the target displacement setting section **11** (in Step **63**).

When the absolute value of the error signal ε between the displacement sensed and the target displacement gets equal to a predetermined value α and when the absolute value of the time differential value $\Delta \varepsilon / \Delta t$ of the error signal ε gets equal to or smaller than a predetermined value β, the servo control section **52** detects the convergence of the control (in

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Step 64). The servo control section 52 outputs the command

values of the voltages V_L and V_R at that point in time to the

voltage value holding section 53. In response, the voltage

value holding section 53 holds these voltage command values V_L

5   and V_R as the command values V_{Li} and V_{Ri} for the moving element

Ai (in Step 65). Also, the switching section 7 switches the

connection of the moving element Ai from the displacement

sensing section 6 to the voltage value holding section 53 (in

Step 66). In this manner, the mode of control on the moving

10   element Ai can be switched from the closed loop control to the

open loop control successfully and the procedure advances to a

closed loop control on the next moving element Ai+1 (in Step

67). When the closed loop control on the nth moving element

An is completed (in Step 68), the intermittent closed loop

15   control routine will complete one cycle.

This intermittent closed loop control routine is carried

out every time the output value of the target displacement

setting section 11 is updated at least. As a result, the

moving elements A1 through An are controlled to their

20   respective desired positions. Optionally, this routine may

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also be carried out at regular intervals.

The microactuator of the preferred embodiment described above performs a closed loop control while making the switching section **7** selectively and cyclically connect the single displacement sensing section **6** and the servo control section **52** to one moving element after another. Once the control has converged on a moving element, the microactuator performs an open loop control on the moving element so as to hold its state. Accordingly, even an actuator with a lot of moving elements can have a significantly reduced number of sensing signal generators, amplifiers and A/D converters for the purpose of displacement sensing. As a result, the circuit size can be reduced and the chip cost can be cut down.

EMBODIMENT 3

Hereinafter, a third preferred embodiment of a microactuator according to the present invention will be described with reference to FIGS. 6 and 7. FIG. 6 illustrates the schematic configuration of a microactuator according to this preferred embodiment.

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In the microactuator of this preferred embodiment, each of the moving section **4**, I/F section **10**, target displacement setting section **11**, displacement sensing control section **14**, first drive voltage generating section **20**, first high-

5 frequency signal generating section **21**, second drive voltage generating section **22**, second high-frequency signal generating section **23**, operational amplifier **24**, capacitor **25**, MOS transistor **26**, amplifier **27** and A/D converter **28** has the same configuration as the counterpart as already described for the

10 second preferred embodiment.

The difference between this and second preferred embodiments lies in the configurations of the switching section **70**, displacement sensing section **71** and control section **75**. In this preferred embodiment, the displacement

15 sensing section **71** additionally has a configuration for extracting only the signal with the frequency **f** from the displacement sensing signal, thereby reducing the offset caused by the variations ΔV_L and ΔV_R in the drive voltages V_L and V_R of the second term on the right side of Equation (1)

20 and increasing the accuracy of the closed loop control. Also,

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once the closed loop control by the servo control section **77** has converged, the switching section **70** disconnects the moving element **Ai** and produces a high impedance state at the terminals T_{Li}, T_{Ri} and T_{Pi}, thereby retaining the charge that has been stored between the electrodes. In this manner, an intermittent closed loop control is carried out simply without using any voltage value holding section.

The switching section **70** includes switches **S1** through **Sn**, which are associated with the moving elements **A1** through **An**, respectively. A switch **Si** is connected to the terminals T_{Li}, T_{Ri} and T_{Pi} of the moving element **Ai**. When turned ON, the switch connects the respective terminals to the driver circuit including the displacement sensing section **71**. On the other hand, the switch in OFF state turns the respective terminals into floating. The ON/OFF states of these three terminals are changed simultaneously.

The displacement sensing section **71** includes not just all components of the counterpart of the second preferred embodiment described above but also an oscillator **72**, a multiplier **73** and a low pass filter **74**. The oscillator **72**

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generates an AC signal having the same frequency f as that of the first high-frequency signal generating section **21**. Also, the AC signal generated by the oscillator **72** has its phase matched with that of the voltage generated by the first high-frequency signal generating section **21**. The multiplier **73** multiplies the outputs of the amplifier **27** and oscillator **72** together. As a result, only a signal component with the frequency f is extracted from the output component of the amplifier **27** and a DC voltage, which is proportional to the amplitude of the signal component with the frequency f, is output. The output of the multiplier **73** is filtered by the low pass filter **74** and then A/D converted by the A/D converter **28**. In this manner, the offset voltage, generated by the variations ΔV_L and ΔV_R in the drive voltages V_L and V_R during the closed loop control, can be reduced and the position sensing accuracy is increased.

The control section **75** includes a voltage command section **76**, which includes a servo control section **77**.

The servo control section **77** receives the difference between the target displacement setting section **11** and the

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displacement sensing section **71** as an error signal ε and carries out a closed loop control on a selected moving element **Ai** by providing the command values of the voltages V_L and V_R as its control outputs.

5   The control section **75** further includes a clock counter (not shown) for counting how long each moving element **Ai** has been connected to the servo control section **77** since its associated **Si** was turned ON in the switching section **70**.

An upper limit value τ is set on the amount of time that

10 can be allotted to the closed loop control on each moving element **Ai**. When the value of the error signal ε and its time differential value get equal to or smaller than predetermined values to converge the control or when the duration of the closed loop control reaches the upper limit

15 value τ , the control section **75** finishes the closed loop control on the moving element **Ai**.   In a normal state, the upper limit value τ is defined large enough to converge the control.   The upper limit value τ may either be a fixed value or reflect the amount of time it took to control the moving

20 element in the past.   For example, if the actual convergence

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time t_{i-1} is shorter than the upper limit value τ of the previous moving element A_{i-1}, then part or all of the extra time $\tau - t_{i-1}$ may be carried over and added to the upper limit value τ of the moving element A_i.

5   When the closed loop control by the servo control section 77 on the moving element A_i is finished, the switching section 70 turns the switch S_i OFF, thereby turning the terminals T_{Li}, T_{Ri} and T_{Pi} into floating. As a result, as long as the loss due to current leakage is sufficiently small, the quantities

10   of charges stored in the capacitors C_{Li} and C_{Ri}, formed by the moving element A_i, are kept constant and the displacement of the moving element A_i is maintained as it was when the closed loop control was finished.

        Then, the switching section 70 turns the next switch S_{i+1}

15   ON and the control section 75 performs a closed loop control on its associated moving element A_{i+1}. In this manner, the closed loop control is carried out time-sequentially on one moving element after another. And when the closed loop control on the last moving element A_n is completed, the

20   processing returns to the first moving element A_1 again and

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the closed loop control of the second cycle is carried out thereon. The period of time of this cycle will be referred to herein as a "frame period". The frame period is determined by the response performance that the microactuator needs to exhibit and a condition to minimize the loss of the quantities of charges stored in the capacitors C_{Li} and C_{Ri} due to the current leakage. The upper limit value τ of the time allotted to each moving element Ai is set such that this frame period satisfies those conditions. For example, if the upper limit value τ is a fixed value, then n $\cdot$ τ will be the frame period. Particularly when the closed loop control is carried out as a digital control, however, the upper limit value τ or the duration ti may be compared by counting the number of times the closed loop control has been carried out repeatedly and comparing the number counted with the maximum number of loops, instead of actually keeping time. Such a loop number management is also essentially a type of time management because the time is managed indirectly. However, the procedure of the management can be simplified.

Hereinafter, it will be described with reference to FIG.

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7 how the microactuator having such a configuration operates. FIG. 7 is a flowchart showing an intermittent closed loop control routine to be done by the microactuator of this preferred embodiment.

5   First, the upper limit value τ is set to an initial value $\tau 0$ (in Step 80). The initial value $\tau 0$ is 1/n of one frame period and is stored in a ROM in advance. Next, by setting $i = 1$, the first moving element **A1** is selected as a moving element **Ai** to be subjected to the closed loop control

10   (in Step 81).

Next, the switching section **70** turns the switch **Si** ON and connects the moving element **Ai** to the displacement sensing section **71** (in Step 82). At this point in time, the switches associated with all of the moving elements but the moving

15   element **Ai** are in OFF state.

The initial control voltage values V_L and V_R of the moving element **Ai** are obtained by getting the output of the target displacement setting section **11** converted by the converting section **12** (in Step 83). The displacement sensing

20   section **71** senses the displacement of the moving element **Ai**

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and the servo control section **77** performs a closed loop

control such that the magnitude of the displacement sensed

matches the target displacement output by the target

displacement setting section **11** (in Step **84**).

5   When the absolute value of the error signal ε between

the displacement sensed and the target displacement gets equal

to a predetermined value α and when the absolute value of the

time differential value $\Delta\varepsilon/\Delta t$ of the error signal ε gets

equal to or smaller than a predetermined value β, the servo

10   control section **77** detects the convergence of the control (in

Step **85**). Unless the convergence is detected, the duration ti

is further compared with the upper limit value τ. And if ti

$<\tau$ is satisfied, then the closed loop control is continued

(in Step **86**).

15   When the convergence is detected or when the duration ti

exceeds the upper limit value, the servo control section **77**

finishes the closed loop control on the moving element **Ai** and

the switching section **70** turns the switch **Si** OFF, thereby

turning the terminals T_{Li}, T_{Ri} and T_{Pi} into floating (in Step

20   **87**).

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Next, the extra time (τ − ti-1) is multiplied by the

coefficient α and the product is carried over to the upper

limit value τ of the processing time of the closed loop

control on the next moving element (in Step **88**). The

5   coefficient α is supposed to be a value satisfying $0 < \alpha < 1$,

thereby preventing the extra time from being carried over and

accumulated infinitely. More preferably, the coefficient α

satisfies $0 < \alpha < \exp(-1/n)$, thereby reducing the degree of

influence of the extra time carried over within one frame

10   period to the predetermined (1/e) or less.

Subsequently, the i value is incremented by one and the

processing advances to a closed loop control on the next

moving element **Ai+1** (in Step **89**). In this manner, the closed

loop control is sequentially carried out on one moving element

15   after another. And when the first cycle is completed (i.e.,

when the closed loop control on the nth moving element **An** is

finished), the second cycle is started by performing a closed

loop control on the first moving element **A1** again (in Step **90**)

The microactuator of the preferred embodiment described

20   above is designed such that when the closed loop control by

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the servo control section **77** has converged, the switching

section **70** disconnects the moving element **A1** and produces a

high impedance state at the terminals T_{L1}, T_{R1} and T_{P1}, thereby

retaining the charge that has been stored between the

5   electrodes. Thus, an intermittent closed loop control can be

carried out cyclically on a lot of moving elements by using a

simple configuration.

In addition, the upper limit value τ is set on the time

that can be allotted to the closed loop control on each moving

10   element. Consequently, the microactuator can have a

sufficient frame period, no matter whether the closed loop

control has converged or not.

Furthermore, this upper limit value τ is defined based

on the amount of time it has taken to carry out the control on

15   the moving elements. As a result, a sufficient frame period

can be guaranteed and the accuracy of the closed loop control

can be improved at the same time.

EMBODIMENT 4

20   A fourth preferred embodiment of a microactuator

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according to the present invention will be described with reference to FIGS. **8** through **10**. The microactuator of this preferred embodiment is an electrostatic actuator for performing a vertical operation and a dual-axis tilting operation, and is applied to a deformable mirror for a compensating optical system.

FIG. **8** is an exploded perspective view of a microactuator according to this preferred embodiment. In FIG. **8**, just one micromirror unit is illustrated on a large scale. The single micromirror unit is given displacement with a degree of freedom of three by three sets of moving elements that can be driven independently of each other, and can perform the vertical and dual-axis tilting operations. Each of those moving elements includes a pair of a yoke and a fixed electrode.

1,024 micromirror units are arranged in total as a two-dimensional array of 32 × 32 micromirror units. The overall number of moving elements, each including a yoke and a fixed electrode as a pair, is 3,072, which is three times as large as the total number of micromirror units.

On a substrate **100**, provided is a driver circuit **100a**, on which an insulating layer **101** has been deposited. And on the insulating layer **101**, a base **102** and three pairs of fixed electrodes **103** to **105** are provided. The base **102** and fixed

5 electrodes **103** to **105** are formed by patterning a conductive film of aluminum (Al), polysilicon or any other suitable material. The fixed electrode **103** includes a first electrode **103L** and a second electrode **103R**, for which voltages can be defined independently of each other. Likewise, the fixed

10 electrode **104** also includes first and second electrodes **104L** and **104R** and the fixed electrode **105** also includes first and second electrodes **105L** and **105R**.

The first and second electrodes **103L**, **104L**, **105L** and **103R**, **104R**, **105R** are connected to the driver circuit **100a** on

15 the substrate **100** by way of via metals (not shown), which are provided in the insulating layer **101**. The driver circuit **100a** can apply mutually independent voltages, all of which fall within the range of 0 V to 30 V, to the first and second electrodes **103L**, **104L**, **105L** and **103R**, **104R**, **105R**. Each of the

20 applied voltages may be set to a multi-bit value of 12 bits,

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for example.

Each of the three yokes **107**, **108** and **109** is secured with a pair of hinges **106**. Furthermore, an intermediate coupling member **111** for coupling these yokes **107**, **108** and **109** to the micromirror **110** is also provided. The hinges **106** are bonded to, and electrically continuous with, the base **102**. Each base **102** is connected to the driver circuit **100a** by way of a via metal (not shown) provided in the insulating layer **101**. Adjacent bases **102** are electrically isolated from each other and are connected to the driver circuit **100a** independently of each other.

These yokes **107**, **108** and **109** face their associated fixed electrodes **103**, **104** and **105**, respectively, so as to function as "movable electrodes". The yokes **107**, **108** and **109** are formed by patterning an electrically conductive material such as aluminum (Al) or polysilicon, and are electrically continuous with the base **102** so as to have the ground potential. Each of these yokes **107**, **108** and **109** has a first portion **107L**, **108L** or **109L** and a second portion **107R**, **108R** or **109R**, which respectively face the first and second electrodes

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103L & 103R, 104L & 104R and 105L & 105R. These yokes 107, 108 and 109 have quite the same shape. Thus, any statement that applies to one of these three yokes automatically applies to the other two unless stated otherwise.

5   The yoke 108 is supported so as to rotate around an axis of rotation A1, while the other yokes 107 and 109 are supported so as to rotate around another axis of rotation A2. Supposing a direction perpendicular to the axis of rotation A1 (or A2) is an x direction and the moving elements are arranged

10 at a pitch p in the x direction, the axes of rotation A1 and A2 are defined so as to shift from each other by a half pitch (=p/2) in the x direction. In this manner, the yokes that are adjacent to each other in the y direction are arranged in a checkerboard pattern so as to shift from each other by the

15 half pitch in the x direction. One of the hinges 106 to support the yoke 107 is provided to extend in the gap between the yoke 108 and the adjacent yoke 108'.

For example, if a drive voltage is applied to the first electrode 103L, then the first portion 107L of the yoke 107

20 will be attracted toward the first electrode 103L. On the

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other hand, if a drive voltage is applied to the second

electrode **103R**, then the second portion **107R** will be attracted

toward the second electrode **103R**. In this manner, the

rotational force can be selectively produced around the axis **A**

5   of rotation either clockwise **CW** or counterclockwise **CCW**.

The yoke **107** is coupled to the protrusion **111a** of the

intermediate coupling member **111** at the drive point **107c**

(indicated by hatching in FIG. **8**) in the vicinity of one free

end of the first portion **107L**. A groove hole **107d** is provided

10 through the yoke **107** near the drive point **107c**.

The intermediate coupling member **111** includes three

protrusions **111a**, **111b** and **111c**, which are coupled to the

drive point **107c** of the yoke **107**, the drive point **108c** of the

yoke **108** and the drive point **109c** of the yoke **109**,

15 respectively. Accordingly, by driving and rotating the yokes

107, **108** and **109** independently of each other, the

displacements of the protrusions **111a**, **111b** and **111c** are

controllable independently and the position of the

intermediate coupling member **111** is fixed. Groove holes **113a**,

20 **113b** and **113c** are bored through the intermediate coupling

member **111** in the vicinity of the protrusions **111a, 111b** and **111c**, respectively.

The micromirror **110** is coupled to the hatched portion **112** of the intermediate coupling member **111** with the protrusion **114**. Since the micromirror **110** and the intermediate coupling member **111** are coupled together, the position of the micromirror **110** is determined by that of the intermediate coupling member **111**. The micromirrors **110** are arranged at a pitch **p** of 100 μm in the x direction and have a mirror length **L** of 98 μm as measured in the x direction.

By applying drive voltages independently to the first electrodes **103L, 104L, 105L** and second electrodes **103R, 104R, 105R**, the micromirror **110** can be driven bidirectionally (i.e., in positive and negative directions), no matter whether the micromirror **110** needs to be displaced in the z direction or tilted around the x axis and/or y axis.

Next, the driver circuit **100a** will be described in detail with reference to FIG. **9**, which shows the schematic configuration of the driver circuit **100a** for the microactuator of this preferred embodiment. A plurality of moving elements,

each consisting of a yoke and two fixed electrodes, are also shown along with the driver circuit **100a** and are identified by $A_{i,j}$. The subscripts i and j respectively represent the row and column addresses thereof in a two-dimensional array of

5 moving elements. A single micromirror unit is made up of three moving elements. Thus, a single micromirror unit is associated with a set of three j values. For example, three moving elements to move the same micromirror are identified by $A_{1,1}$, $A_{1,2}$ and $A_{1,3}$. The micromirror units are arranged as a

10 32×32 array. Thus, i is a natural number falling within the range of 1 through 32 and j is a natural number falling within the range of 1 through 96.

Six MOS transistors are connected as switching elements to each moving element $A_{i,j}$. Each of these MOS transistors

15 operates in the enhancement mode. Thus, the switch is turned ON when its gate voltage is increased to H level but turned OFF when its gate voltage is decreased to L level. To minimize the loss of voltage by each MOS transistor, the gate voltage used is boosted by a booster (not shown).

20 Among the six MOS transistors, the lower three MOS

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transistors are used to carry out an open loop control on the moving element $A1,j$. When a driving word line $WD1$ is raised to H level, the three transistors respectively connect driving bit lines BDj_L, BDj_R and BDj_P to the first electrode, second

5 electrode and yoke of the moving element $A1,j$.

On the other hand, the upper three MOS transistors are used to sense the displacement of the moving element $A1,j$ and calibrate the relationship between the voltage and the displacement. When a sensing word line $WS1$ is raised to H

10 level, the three transistors respectively connect sensing bit lines BSj_L, BSj_R and BSj_P to the first electrode, second electrode and yoke of the moving element Ai,j.

The driving word lines $WD1$ through $WD32$ and the sensing word lines $WS1$ through $WS32$ are connected to a line decoder

15 120. Only a word line that has been selected in response to an address signal $Adr1$ supplied from a switching control section 121 is raised to H level. The line decoder 120 is implemented as a demultiplexer.

The configuration will be further described along the

20 flow of signals during the open loop control operation.

An I/F section **122** exchanges commands and data with an external control device. The externally input data includes data about the shape of the wavefront to be defined by the deformable mirror. This wavefront shape data is given either

5   as data representing displacement in z direction at each coordinate point on an xy plane or as wavefront mode coefficient data by a Zernike polynomial, for example. To reduce the transfer load, each of these types of data may be compressed before being transmitted. Examples of imaginable

10   methods include an intra-frame compression method in which the wavefront shape is compressed within the given frame, an inter-frame compression method in which the difference between the wavefront shapes at the previous and current times is calculated, and a method in which two types of data compressed

15   by these two methods are alternately transferred on a predetermined number of frames basis. Alternatively, in a simpler configuration, a desired one may be called up from multiple types of pre-registered wavefront shapes. In that case, the externally input data is the registration number of

20   the wavefront shape.

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In accordance with the output of the I/F section **122**, a target displacement setting section **123** generates target displacement data $Z_{i,j}$ specifying the target displacement of each moving element $A_{i,j}$. Each item of target displacement

5 data $Z_{i,j}$ is 20-bit data consisting of a 12-bit part representing the i and j addresses and an 8-bit part representing the magnitude of the target displacement in 256 stages from -128 through 127. The target displacement setting section **123** outputs one item of target displacement data $Z_{i,j}$

10 after another to a converting section **124** while incrementing the j value first. And when the j value reaches the maximum value of 96, the target displacement setting section **123** will increment the i value. Consequently, the target displacement data is output in the order of $Z_{1,1}$, $Z_{1,2}$, ..., $Z_{1,96}$, $Z_{2,1}$, $Z_{2,2}$ and

15 so on.

The converting section **124** includes a conversion table, which outputs voltage command data $D_{i,j}$ corresponding to the target displacement data $Z_{i,j}$ that has been input there as an address. The voltage command data $D_{i,j}$ is 11-bit data that

20 takes one of 2,048 values of -1024 through 1023, and the most

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significant bit thereof represents its sign (i.e., positive or negative). That is to say, the most significant bit shows whether the fixed electrode to drive is the first electrode of the moving element **Ai,j** or the second electrode thereof. This

5   conversion table is drawn up by a calibrating section **134** and then stored in a rewritable memory in the converting section **124**. The voltage command data **Di,j** is supplied to a shift register **125** bit by bit. No sooner has the voltage command data **Di,j** been transferred to the shift register **125** than the

10   voltage command data **Di,j+1** of the next moving element **Ai,j+1** starts to be transferred.

The shift register **125** sequentially transfers the voltage command data **Di,j**, supplied from the converting section **124**, on a bit-by-bit basis. When the voltage command data **Di,1**

15   through **Di,96** associated with the moving elements **Ai,1** through **Ai,96**, respectively, have been transferred, the switching section **121** will output a strobe signal **Stb** to a latch **126**. At this timing, the voltage command data **Di,1** through **Di,96** in the shift register **125** gets stored on the latch **126** at the

20   same time. The shift register **125** has a transfer rate of

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16.9 MHz and transfers 96 data items, each consisting of 11

bits, in 62.5 μs. On transferring the data to the latch **126**,

the shift register **125** starts to transfer the data associated

with the moving elements **Ai+1,1** through **Ai+1,96** on the next

5   row. Accordingly, the latch **126** receives the strobe signal

Stb in a period of about 62.5 μs, which corresponds to the

period in which the voltage is applied to the moving elements

Ai,1 through **Ai,96**.

The voltage command data **Di,1** through **Di,96** stored in the

10   latch **126** is converted by 96 D/A converters **127** and 96

switches **128** into drive voltages to be applied to the fixed

electrodes of respective moving elements **Ai,j**. In the

following description, only the D/A converter **127a** and switch

128a, which are associated with the moving element **Ai,1**, will

15   be described as an example. However, each of the other 95 D/A

converters or switches has the same configuration as its

counterpart.

The D/A converter **127a** is a 10-bit D/A converter, which

receives the lower 10 bits of the 11-bit voltage command data

20   **Di,1** and outputs a drive voltage of an associated magnitude

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that varies from 0 V through 30 V.

The switch 128a receives the most significant bit of the 11-bit voltage command data $D_{1,1}$ and connects a driving bit line BD_{1L} to ground potential and a driving bit line BD_{1R} to the output of the D/A converter 127a, respectively, if the most significant bit is zero. On the other hand, if the most significant bit is one, the switch 128a connects the driving bit line BD_{1L} to the output of the D/A converter 127a and the driving bit line BD_{1R} to ground potential, respectively. As a result, if the target displacement of the moving element $A_{1,1}$ has a positive value, the output of the D/A converter 127a is connected to the second electrode thereof. Meanwhile, if the target displacement has a negative value, the output of the D/A converter 127a is connected to the first electrode thereof. Consequently, the tilt of the moving element can be controlled bidirectionally (i.e., both in the positive and negative directions).

In this manner, each switch 128 selects one of two driving bit lines BD_{1L} and BD_{1R} in an associated one of 96 pairs and applies the drive voltage, supplied from its

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associated D/A converter **127**, to that driving bit line.

At the same time, the switching control section **121**
supplies an address signal **Adrl**, which selectively turns only
an ith driving word line **WDi** into H level, to the line decoder
5   **120**. When the driving word line **WDi** is raised to H level, the
moving elements **Ai,1** through **Ai,96** become electrically
continuous with the driving bit lines BD_{iL}, BD_{iR} and BD_{iP}. As a
result, an open loop control is carried out according to the
magnitude of target displacement. As described above, the
10   period of time in which the drive voltage is applied to the
moving elements **Ai,1** through **Ai,96** is 62.5 μ s. Meanwhile,
the moving elements **Ai,j** have primary resonance frequencies of
70 kHz to 100 kHz and response times of about 10 μ s to about
14 μ s, which are obtained as their inverse numbers.   In this
15   manner, the period of time in which the drive voltage is
applied to the moving elements is defined sufficiently longer
than the response times of the moving elements.   Thus, the
drive   voltage   can   be   applied   continuously   until   the
displacements   of   the   moving   elements   have   been   settled
20   sufficiently.   As   a   result,   it   is   possible   to   prevent   the

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voltage between the electrodes from being varied significantly due to the displacements of the moving elements after the drive voltage has been applied thereto.   Consequently, the moving elements can be displaced more precisely during the

5   open loop control.

In this manner, during the open loop control, the i value is incremented in a period of 62.5 μ s and desired displacements are produced in the moving elements **Ai,1** through **Ai,96** on each row.   The amount of time it takes to carry out

10   the open loop control on the moving elements of all 32 rows is 2 ms, which is one frame period.

Hereinafter, the configuration will be further described along the flow of signals during the calibrating operation. The calibrating operation is carried out when the system is

15   started, for example.   The basic flow of the calibrating operation is similar to that already described for the first preferred embodiment.   The main differences between this and first preferred embodiments lie in that the position sensing accuracy is increased by eliminating the offset caused by the

20   parasitic capacitance of lines, for example, and that the

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inverting output is eliminated by applying a bias voltage V_A to the output of the D/A converter **131** and to the differential input of the displacement sensing section **133**.

The voltage command section **130** generates voltage command

5   values for two channels and supplies the outputs of these channels to the D/A converters **131a** and **131b** while switching those channels at a frequency of about 1 MHz to about 10 MHz. As a result, the D/A converter **131a** outputs a voltage $V_L + V_A$ (1 $+ \sin(2\pi ft)$), while the D/A converter **131b** outputs a voltage

10   $V_R + V_A$ (1 $- \sin(2\pi ft)$). Actually, the waveform of this AC voltage component with the amplitude V_A and the frequency f is preferably not so much a sine wave as a rectangular wave. During the calibrating operation, the voltage command section **130** keeps the V_A value constant most of the time, sets one of

15   the drive voltages V_L and V_R equal to 0 V, and changes the other drive voltage in multiple stages. That is to say, this is a configuration obtained by additionally providing the bias voltage V_A for the configuration already described for the first preferred embodiment. And the output voltages of the

20   D/A converters **131a** and **131b** are always positive.

In response to an address signal **Adr2** supplied from the switching control section **121**, a switching section **132** connects the sensing bit lines **BSj$_L$**, **BSj$_R$** and **BSj$_P$** of the jth column to the D/A converters **131a** and **131b** and displacement

5   sensing section **133**, respectively.

Meanwhile, in response to the address signal **Adr1** supplied from the switching control section **121**, the line decoder **120** turns the sensing word line **WSi** of the ith row into H level. As a result, the sensing bit lines **BSj$_L$**, **BSj$_R$**

10 and **BSj$_P$** are respectively connected to the first electrode, second electrode and yoke of the moving element **Ai,j**. In this manner, the first electrode, second electrode and yoke of a single selected moving element **Ai,j** are connected to the D/A converters **131a** and **131b** and displacement sensing section **133**,

15 respectively.

The configuration of the displacement sensing section **133** is basically the same as that of the displacement sensing section **71** of the third preferred embodiment described above. In this preferred embodiment, however, the bias voltage **V$_A$** is

20 applied to the non-inverting input of a first-stage

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differential amplifier **133a**. In this manner, the bias voltage

V_A applied by the D/A converter **131** can be compensated for and

the potential level relationship among the first electrode,

second electrode and yoke of the moving element **Ai,j** during

5   the open loop control can be maintained, and the decrease in

calibrating precision can be minimized.

The calibrating section **134** receives the voltage command

value   from   the   voltage   command   section   **130**   and   the

displacement of the moving element **Ai,j** that has been sensed

10   by the displacement sensing section **133**, thereby defining the

correlation   between   the   voltage   command   value   and   the

displacement.   Measuring   errors   can   be   removed   from   these

relationships by fitting them with an approximation curve of a

predetermined   format.   Then,   resultant   interpolated

15   relationships   are   stored   in   the   conversion   table   of   the

converting section **124**.

Hereinafter, it will be described with reference to FIG.

10 how the microactuator with such a configuration operates.

FIG.   **10**   is   a   flowchart   showing   the   calibrating   operation

20   routine   to   be   done   by   the   microactuator   of   this   preferred

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embodiment.

First, by setting $j = 1$ (in Step **140**), the switching
section **132** connects the sensing bit lines **BSj$_L$**, **BSj$_R$** and **BSj$_P$**
of the jth column to the D/A converters **131a** and **131b** and
displacement sensing section **133**, respectively (in Step **141**).
Next, by setting $i=1$ (in Step **142**), the switching section **132**
selects the moving element **A1,j** as the object of displacement
sensing. The voltage command section **130** sets the voltage
command value **D** equal to its minimum value **Dmin** (in Step **143**).
In this case, the drive voltages V_R and V_L are defined to be 0
V and 30 V, respectively, and the difference $V_R - V_L$ between
them becomes equal to the lowest voltage of -30 V. In the
following description, if the voltage command value **D** is
negative, then $V_R = 0$ V and V_L is set to a positive value. On
the other hand, if D is positive, then $V_L = 0$ V and V_R is set to
a positive value. As already described, a high frequency
signal has been superposed thereon for the purpose of
displacement sensing.

Before the displacement of the moving element **A1,j** is
sensed, the switching control section **121** turns all of the

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sensing word lines **WS1** through **WS32** into L level, thereby

disconnecting all of the moving elements **A1,j** through **A32,j**

from the sensing bit lines **BSj$_L$**, **BSj$_R$** and **BSj$_P$** (in Step **144**).

The calibrating section **134** stores the output of the

5   displacement sensing section **133** at this point in time as an

offset value Z0(D) (in Step **145**). Since the moving elements

have been disconnected, the offset value Z0(D) represents the

error component produced by the parasitic capacitance of lines

or the drive voltages. It should be noted that these

10 processing steps **144** and **145** are carried out only when i$=$1.

Subsequently, the switching control section **121** turns the

sensing word line **WS1** into H level, thereby connecting the

moving element **A1,j** to the sensing bit lines **BSj$_L$**, **BSj$_R$** and

BSj$_P$ (in Step **146**). The calibrating section **134** stores the

15 output of the displacement sensing section **133** at this point

in time as an uncorrected displacement Z'(D) (in Step **147**).

Then, the calibrating section **134** calculates a corrected

displacement Z(D) from the uncorrected displacement Z'(D) and

the offset value Z0(D) and stores it (in Step **148**). Normally,

20 Z(D)$=$Z'(D)$-$Z0(D) may be satisfied. However, the offset may

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also be corrected by using another correction equation obtained through experiments, for example.

Next, the voltage command value D is increased by a predetermined value (in Step 149). Thereafter, the displacement Z(D) is repeatedly measured until D gets equal to the maximum value **Dmax** (in Step 150). As a result, the displacements Z(D) measured with respect to the D values in multiple stages are stored in the calibrating section 134. The calibrating section 134 eliminates the measuring errors by fitting those values to a predetermined approximation function and obtains an 11-bit voltage command value D for each displacement (Z) value of eight bits while interpolating them with this approximation function. By adding 12-bit data representing the i, j addresses of the moving element **Ai,j** thereto, a conversion table, showing relationships between the displacement Z and voltage command value D of the moving element **Ai,j**, can be obtained (in Step 151).

Next, i is incremented (in Step 152) and a conversion table, showing relationships between the displacement Z and voltage command value D of the 32 moving elements **Al,j** through

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A32,j of the same j^{th} column, is drawn up in the same way (in Step 153).

Subsequently, j is incremented (in Step 154) and conversion tables, showing relationships between the displacement Z and the voltage command value D, are compiled for all of the moving elements on the 96 columns (in Step 155).

FIGS. 11(a) and 11(b) are graphs showing correlations between the voltage command value D and displacement of a moving element. In FIG. 11(a), data about the offset correction is shown. The data points indicated by the crosses X in FIG. 11(a) represent the offset values Z0(D) measured. The data points indicated by the open triangles △ there represent the uncorrected displacements Z'(D) measured. And the data points indicated by the open circles ○ there represent the corrected displacements Z(D) calculated according to the equation $Z(D)=Z'(D)-Z0(D)$.

In this preferred embodiment, with the voltage command value D changed in thirteen stages, the displacement Z(D) is calculated with respect to each of those voltage command

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values **D**.   The increases of the voltage command values **D** are

not constant in their respective stages.   Specifically, the

closer to Dmax or Dmin the given voltage command value **D**, the

greater the variation in displacement Z'(D) with respect to

5   the voltage command value **D**.   For that reason, the closer to

Dmax or Dmin the voltage command value **D** gets, the smaller its

increase is defined.   By defining the increase of the voltage

command value **D** in this manner with the nonlinear relationship

between the voltage command value **D** and the displacement Z'(D)

10   taken into account, the displacement Z'(D) can be increased

substantially constantly.

In FIG. **11(b)**, the offset-corrected displacements Z(D)

that have been fitted with an approximation function are

represented as a solid curve.   The approximation function used

15   here is a quadratic function $Z(D) = \alpha D^2 + \beta D + \gamma$.   In each of

the quadrant in which $D > 0$ and the quadrant in which $D < 0$, the

values of the coefficients α, β and γ are determined so as

to minimize the fitting errors.   In FIG. **11(b)**, the

correlation between the voltage command value **D** yet to be

20   calibrated and the displacement **Z** is represented as a dashed

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curve for reference.

As described above, the displacement Z calculated with the moving element $A_{i,j}$ connected to the sensing bit lines BS_{j_L}, BS_{j_R} and BS_{j_P} or any other lines is corrected with the offset value Z_0 obtained with the moving element $A_{i,j}$ disconnected from these lines. As a result, the unwanted effects of the offset due to the parasitic capacitance of the lines can be eliminated and the position sensing accuracy of the moving element $A_{i,j}$ can be increased.

In the preferred embodiment described above, the displacements of the moving elements are sensed with those moving elements disconnected one after another. Alternatively, the displacements of those moving elements may be sensed simultaneously by providing a plurality of circuit sections, each including the voltage command section 130, D/A converters 131a, 131b and displacement sensing section 133. In particular, if three moving elements belonging to a single micromirror unit are driven simultaneously and their displacements are sensed and calibrated in the meantime, then the control operation can be carried out so as to compensate

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for even a crosstalk displacement that might happen when the driving force is transmitted among the moving elements. In that case, the conversion table to be made by the calibrating section **134** will output a voltage command value **D1,1** for a

5   moving element **A1,1** on receiving an address including three pieces of information about the displacement (Z1, 1) of the moving element **A1,1**, the displacement (Z1, 2) of another moving element **A1,2** and the displacement (Z1, 3) of still another moving element **A1,3**. If the voltage command value

10   **D1,1** is affected by the displacements (Z1, 2) and (Z1, 3) to a relatively small degree, then the displacements (Z1, 2) and (Z1, 3) may have only their high-order bits.

EMBODIMENT 5

15   Hereinafter, a fifth preferred embodiment of a microactuator according to the present invention will be described with reference to FIG. **12**, which illustrates the schematic configuration of a microactuator according to this preferred embodiment.

20   The control section **75** of the microactuator of this

preferred embodiment has the same configuration as the control

section **75** of the microactuator of the third preferred

embodiment described above.   The microactuator of this

preferred embodiment is different from the counterpart of the

5   third preferred embodiment in the configurations of the moving

section **160**, switching section **161** and displacement sensing

section **162**.   Hereinafter, these configurations will be

described.

In this preferred embodiment, the line arrangements of

10   the moving section **160** and switching section **161** for sensing

the displacement are simplified.   Each movable electrode Y_{Li}

of the moving section **160** is disconnected from the switching

section **161** and grounded.   Accordingly, each switch **S1** of the

switching section **161** includes a switch connected to the fixed

15   electrode E_{Li} and a switch connected to the fixed electrode E_{Ri}

but no switch connected to the movable electrode Y_{Li}.

As shown in FIG. 12, the displacement sensing section **162**

includes a high-frequency signal generating section **21**, load

resistors **163L** and **163R**, isolators **164L** and **164R**, high pass

20   filters **165L** and **165R**, a high-frequency phase difference

detecting section **166** and an A/D converter **167**.

One terminal of the load resistor **163L** will be referred to herein as a "first terminal T_L". The first terminal T_L is connected to the fixed electrode E_{L1} of the moving element **A1** by way of the switch **S1** of the switching section **161**. To the other terminal of the load resistor **163L**, the sum signal $V_L + V_A \sin(2\pi ft)$ of the drive signal V_L supplied from the first drive voltage generating section **20** and the high-frequency signal $V_A \sin(2\pi ft)$ supplied from the high-frequency signal generating section **21** is applied.

In the same way, one terminal of the load resistor **163R** will be referred to herein as a "second terminal T_R". The second terminal T_R is connected to the fixed electrode E_{R1} of the moving element **A1** by way of the switch **S1** of the switching section **161**. To the other terminal of the load resistor **163R**, the sum signal $V_R + V_A \sin(2\pi ft)$ of the drive signal V_R supplied from the second drive voltage generating section **22** and the high-frequency signal $V_A \sin(2\pi ft)$ supplied from the high-frequency signal generating section **21** is applied.

The load resistors **163L** and **163R** have the same impedance

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Z_0 with respect to the high-frequency signal $V_A \sin(2\pi ft)$. In this case, this impedance Z_0 is supposed to be pure resistance with no imaginary part and have a value including the internal resistance of the first and second drive voltage generating

5   sections 20 and 22.

The magnitude of the impedance Z_0 is determined so as to satisfy $0.5 < 2\pi fCZ_0 < 2$, where C is the electrostatic capacitance of the capacitors C_{L1} and C_{R1} when the moving element A1 is not displaced. For example, if C is 10 fF, then

10   f is set to 100 MHz and Z_0 is set to 160 kΩ. By defining the impedance Z_0 within such a range, the displacement sensitivity can be substantially maximized.

The isolators 164L and 164R are connected to the first and second terminals T_L and T_R, respectively, to carry out

15   impedance conversion. Each of these isolators 164L and 164R is implemented as a voltage follower using an operational amplifier. The outputs of the isolators 164L and 164R are input to the high-frequency phase difference detecting section 166 by way of the high pass filters 165L and 165R,

20   respectively. The high pass filters 165L and 165R transmit

sufficiently a high-frequency component having the frequency f and blocks sufficiently a low-frequency component of the drive signals V_L and V_R.

The high-frequency phase difference detecting section **166** detects the phase difference between the incoming two high-frequency signals and outputs a signal representing the phase difference. The output of the high-frequency phase difference detecting section **166** is converted into digital data by the A/D converter **167**. This digital data represents the difference between the capacitances of the capacitors C_{Li} and C_{Ri}, i.e., the magnitude of displacement of the moving element **Ai**.

These isolators **164L**, **164R**, high pass filters **165L**, **165R**, high-frequency phase difference detecting section **166** and A/D converter **167** together function as a "high-frequency detecting section" in the microactuator of the present invention.

If the drive signals V_L and V_R supplied from the first and second drive voltage generating sections **20** and **22** have mutually different amplitude values in accordance with the instruction of the control section **75**, then the moving element

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A1 is displaced. As a result, a difference is created between the capacitances of the capacitors C_{L1} and C_{R1}, which generates a phase difference with a high-frequency component having the frequency f between the first and second terminals T_L and T_R as described above. Accordingly, the displacement can be sensed without connecting each movable electrode Y_{L1} to the displacement sensing section **162**.

It should be noted that the drive signal has a frequency that is equal to or lower than the primary resonance frequency of the moving element **A1**. The drive signal used in this preferred embodiment is a direct current voltage. Accordingly, in this preferred embodiment, the magnitude of the drive signal means a voltage value. The high frequency signal has a frequency that is equal to or higher than the primary resonance frequency of the moving element **A1**.

In the microactuator of the preferred embodiment described above, the displacement sensing section **162** includes the high frequency signal generating section **21**, the first load resistor **163L** connected to the first electrode E_{L1} at the first terminal T_L, the second load resistor **163R** connected to

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the second electrode E_{Ri} at the second terminal T_R, and the high frequency detecting section **164** through **167** connected to the first and second terminals T_L and T_R. To the other terminal of the first load resistor **163L**, a first sum signal

5    $V_L + V_A \sin(2\pi ft)$, generated by superposing the high-frequency signal $V_A \sin(2\pi ft)$ on the first drive signal V_L, is applied. To the other terminal of the second load resistor **163R** on the other hand, a second sum signal $V_R + V_A \sin(2\pi ft)$, generated by superposing the high-frequency signal $V_A \sin(2\pi ft)$ on the

10   second drive signal V_R having a different magnitude from the first drive signal V_L, is applied. And the high frequency detecting section **164** through **167** is designed so as to detect the phase difference of the high frequency signal between the first and second terminals T_L and T_R. Thus, there is no need

15   to connect the movable electrodes Y_i to the displacement sensing section **162** one by one and the line arrangements of the moving section **160** and the switching section **161** can be simplified significantly.

In addition, according to the configuration of this

20   preferred embodiment, just one high frequency signal

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generating section **21** needs to be provided and the second high

frequency signal generating section **23** for inverting the phase

may be omitted.

Furthermore, in the preferred embodiment described above,

5   the load resistors **163L** and **163R** have fixed impedance.

However, one of the load resistors **163L** and **163R** (e.g., the

load resistor **163L**) may have variable impedance.   In that

case, by adjusting the impedance of the load resistor **163L**

such that the frequency **f** of the differential voltage between

10   the terminals T_L and T_R has zero component, the capacitance

difference between the capacitors C_{Li} and C_{Ri} can be detected.

Also, in the preferred embodiment described above, the

load resistors **163L** and **163R** are supposed to have pure

resistance with no imaginary part.   However, the present

15   invention is in no way limited to that specific preferred

embodiment. Alternatively, a coil, a capacitor and so on may

be used either by themselves or in combination with a resistor

such that the resistance value has an imaginary part.

Particularly when a resonator circuit configuration is used,

20   the phase sensitivity can be increased significantly.

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In the microactuator of the present invention, the "load impedance element" does not have to be the "load resistor" of this preferred embodiment but may also be an element with a load impedance formed by the coil, capacitor and so on as

5 described above.

The high frequency phase difference detecting section **166** for detecting the phase difference between the incoming two high frequency signals may be replaced with a configuration for detecting either the amplitude difference or amplitude

10 ratio between the incoming two high frequency signals. In the microactuator of the present invention, the "high frequency detecting section" may have any arbitrary configuration for comparing the phases and/or amplitudes of the incoming two high frequency signals.

15 The difference between the circuit configuration of the displacement sensing section **162** of this preferred embodiment and that of an ordinary impedance bridging circuit will be described again supplementally. The circuit configuration of the displacement sensing section **162** is characterized by being

20 symmetric with respect to only a high frequency signal and

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asymmetric with respect to a low frequency signal. That is to

say, the first and second drive voltage generating sections **20**

and **22**, provided within the impedance bridging circuit, can

generate mutually different drive voltages. By adopting such

5   an asymmetric circuit configuration for a low frequency

signal, the movable electrode of the moving element **A1** can be

displaced with the magnitude of its displacement sensed. On

the other hand, the circuit configuration is symmetric with

respect to a high frequency signal. Consequently, the very

10   small capacitance difference between the capacitors C_{L1} and C_{R1}

can be detected precisely with the differential signal between

the terminals T_L and T_R.

EMBODIMENT 6

15   Hereinafter, a sixth preferred embodiment of a

microactuator according to the present invention will be

described with reference to FIGS. **13** and **14**. FIG. **13**

illustrates the schematic configuration of a microactuator

according to this preferred embodiment.

20   In the microactuator of this preferred embodiment, each

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of the moving element **Ai,j**, I/F section **122** and target

displacement setting section **123** has the same configuration as

the counterpart of the microactuator of the fourth preferred

embodiment described above. Also, the displacement sensing

5   section **170** is obtained by arranging a plurality of

displacement sensing sections **162** of the microactuator of the

fifth preferred embodiment.

The configuration of this preferred embodiment is

different from that of the fourth or fifth preferred

10   embodiment described above in that a nonlinear D/A converter

176 is used to convert a voltage command value **Di,j** into drive

voltages $V_{i,jL}$ and $V_{i,jR}$, thereby compensating for the non-

linearity of the relationship between the drive voltages $V_{i,jL}$

and $V_{i,jR}$ and the displacement of the moving element and

15   establishing a substantially linear relationship between the

voltage command value **Di,j** and the displacement of the moving

element.   As a result, the number of bits of the voltage

command value **Di,j** to achieve a required displacement

resolution can be reduced.   In addition, the computational

20   complexity can be reduced significantly as well when the

calibrating section **178** fits the correlation between the voltage command value **Di,j** and the moving element to an approximation function.

Two switching MOS transistors are connected to each

5   moving element **Ai,j**. When a word line **Wi** is turned into H level, its associated bit lines **BjL** and **BjR** become electrically continuous with the first and second electrodes of its associated moving element **Ai,j**.

The word lines **W1** to **W32** are connected to a line decoder

10   **171** and only one of the word lines that has been selected in response to an address signal **Adrl** from a switching control section **172** is turned into H level.

A converting section **173**, a shift register **174** and a latch **175** work in quite the same way as the converting section

15   **124**, shift register **125** and latch **126** of the fourth preferred embodiment described above except that the number of bits of the voltage command value **Di,j** to process is nine. Specifically, the converting section **124**, shift register **125** and latch **126** process a voltage command value of 11 bits.

Thus, the configuration of this preferred embodiment is rougher than that of the fourth preferred embodiment by 2 bits. However, a substantially linear relationship is established between the voltage command value $D_{i,j}$ and the displacement of

5   the moving element by using the D/A converter 176 as will be described later. For that reason, similar resolution is realized for the displacement of the moving element. Also, as described for the fourth preferred embodiment, the most significant bit of the 9-bit voltage command value $D_{i,j}$

10   represents whether the fixed electrode to drive is the first electrode of the moving element $A_{i,j}$ or the second electrode thereof. The shift register 174 has a transfer rate of 13.8 MHz and transfers 96 data items, each consisting of 9 bits, in 62.5 μs.

15   The voltage command values $D_{i,1}$ through $D_{i,96}$ held in the latch 175 are converted by 96 nonlinear D/A converters 176 into drive voltages $V_{i,jL}$ and $V_{i,jR}$ to be applied to the respective fixed electrodes of each moving element $A_{i,j}$. Each nonlinear D/A converter 176 outputs a drive voltage,

20   corresponding to the lower eight bits of its associated

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voltage command value $D_{i,j}$, to one of its associated bit lines B_{jL} and B_{jR} that has been selected according to the most significant bit of the voltage command value $D_{i,j}$. A predetermined nonlinear correlation is established between the value of these lower eight bits and the magnitude of the drive voltage. This nonlinear correlation is defined so as to compensate for the non-linearity of the relationship between the drive voltage and the displacement of the moving element and establish a linear relationship between the voltage command value $D_{i,j}$ and the displacement of the moving element. These nonlinear D/A converters 176 will be described more fully later.

When the line decoder 171 turns only an ith word line W_i into H level, the respective moving elements $A_{i,j}$ become electrically continuous with their associated bit lines B_{iL} and B_{iR} and the displacements of the respective moving elements $A_{i,j}$ are subjected to an open loop control in accordance with the voltage command values $D_{i,j}$.

In performing the calibrating operation, the displacement

sensing section **170** senses the displacement while changing

this voltage command value **Di,j** in multiple stages.   The

output of the displacement sensing section **170** is supplied to

a calibrating section **178**, which compiles a correction table

5   by associating the output with a voltage command value **Di,j**.

This operation is basically the same as that described for the

fourth preferred embodiment as well as the offset correction.

The difference between this and fourth preferred embodiments

lies in that a linear function $D(Z) = \alpha Z + \beta$ is used during the

10   fitting operation with the approximation function.

Hereinafter, the configuration of the nonlinear D/A

converter **176** and the linear function approximating operation

of the calibrating section **178** will be described with

reference to FIG. **14**.

15   FIG. **14(a)** schematically illustrates the configuration of

the nonlinear D/A converter **176**.   The configuration of a

single nonlinear D/A converter **176a** will be described herein

as an example but the other 95 converters have the same

configuration.   It should be noted that the subscripts i, j,

representing with which moving element a given voltage command value is associated as in Di,j, are omitted for the sake of simplicity. Thus, every voltage command value will be identified by D, every pair of drive voltages output to the first and second electrodes by V_L and V_R, and every pair of bit lines by B_L and B_R, respectively.

Supposing the potential levels at both terminals of a serial connection of resistors **R1** through **Rn-1** are the lowest potential **V1** and the highest potential **Vn**, respectively, the nonlinear D/A converter **176a** generates a number n of potentials **V1** through **Vn** including intermediate potentials resulting from resistor voltage division. And a selector **180** selectively outputs an appropriate one of these n potentials **V1** through **Vn**. In this example, the lowest potential **V1** is supposed to be ground potential. Also, since the nonlinear D/A converter **176a** has a bit precision of 8 bits, the n value is 256 in this example.

Receiving the 9-bit voltage command value **D**, the selector **180** outputs its associated drive voltages V_L and V_R to the bit

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lines B_L and B_R, respectively. If the most significant bit of the voltage command value D is zero, then the lowest potential V1 is selected as the drive voltage V_L and one of the potentials V1 through Vn, corresponding to the lower eight bits of the voltage command value D, is selected as the drive voltage V_R. On the other hand, if the most significant bit is one, then one of the potentials V1 through Vn, corresponding to the lower eight bits of the voltage command value D, is selected as the drive voltage V_L and the lowest potential V1 is selected as the drive voltage V_R. In the following description, the sign of the voltage command value D is supposed to be positive when the most significant bit thereof is zero and negative when the most significant bit thereof is one. Also, the drive voltage V is defined as $V = V_R - V_L$ and given the positive or negative sign just like the voltage command value D.

The resistance values of the resistors R1 through Rn-1 are defined so as to include at least two mutually different ones. By setting these resistance values appropriately, arbitrary non-linearity is achieved. More specifically, if

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the resistor, located closest to the terminal to which the

lowest potential **V1** is connected, is identified by R1 and the

other resistors are sequentially identified by R2, R3, … and

Rn-1, respectively, their resistance values are defined so as

5   to decrease in the descending order (i.e., R1$>$R2$>$R3$>$ … $>$R-

1).   By adopting such settings, the greater the potential

value **Vi** (where i $=$ 2 through n), the smaller the potential

increase Vi$-$Vi-1.   That is to say, the greater the absolute

value of the drive voltage **V**, the smaller the increase in

10   drive voltage **V** with respect to the increase in voltage

command value **D**.

The drive voltage **V** and the displacement **Z** of the moving

element satisfy such a relationship that the greater the

absolute value of the drive voltage **V**, the greater the

15   increase in displacement **Z** with respect to the increase in the

drive voltage **V**.   Thus, by giving the D/A converter **176** the

nonlinear characteristic described above, the nonlinear

characteristic between the drive voltage **V** of the moving

element and the displacement **Z** can be compensated for and the

20   relationship between the voltage command value **D** and the

displacement **Z** of the moving element can be made closer to a linear one.

More preferably, the resistance values of the resistors **R1** through **Rn** are defined such that the function V(D) of the voltage command value **D** and the drive voltage **V** satisfy the equation $|V| = k \cdot |D|^{1/2}$ (where k is a constant).

FIG. **14(b)** is a set of graphs showing correlations between the voltage command value **D** and the displacement **Z** in the calibrating section **178**.

Specifically, the graph **(A)** on the upper right side of FIG. **14(b)** shows a function V(D) representing the characteristic between the voltage command value **D** and the drive voltage **V** of the nonlinear D/A converter **176**. As described above, this function is defined so as to satisfy the equation $|V| = k \cdot |D|^{1/2}$. More exactly, the nonlinear relationship is defined so as to satisfy $V = k \cdot D^{1/2}$ if the voltage command value **D** is positive and $V = -k \cdot (-D)^{1/2}$ if the voltage command value **D** is negative, respectively. This characteristic is determined by the resistors **R1** through **Rn-1**

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of the nonlinear D/A converter **176**, and therefore, is fixed and not modifiable by any external operation.

The graph **(B)** on the upper left side of FIG. **14(b)** shows a function Z1(V) representing the characteristic between the drive voltage **V** and the displacement **Z** of a moving element **A1** as a solid curve and a function Z2(V) representing the characteristic between the drive voltage **V** and the displacement **Z** of another moving element **A2** as a dashed curve, respectively. The differences between these moving elements **A1** and **A2** include not only a variation in characteristic among the respective moving elements but also a variation in the characteristic of the same moving element with time or according to the environment, for example. This graph shows only two different characteristic functions. Actually, however, there are more characteristic functions. This characteristic is determined by the specific state of the moving element, and therefore, is fixed and not modifiable by any external operation, either.

The graph **(C)** on the lower left side of FIG. **14(b)** shows

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the calibrating functions D1(Z) and D2(Z) defined by the calibrating section **178** to calibrate the characteristics of these moving elements **A1** and **A2**. More specifically, the calibrating function D1(Z) represents the relationship between the displacement **Z** and the voltage command value **D** of the moving element **A1** by a solid line. On the other hand, the calibrating function D2(Z) represents the relationship between the displacement **Z** and the voltage command value **D** of the moving element **A2** by a dashed line. These calibrating functions D1(Z) and D2(Z) can be updated arbitrarily through a calibrating operation.

Hereinafter, it will be described how the displacements **Z** are sensed with the voltage command value **D** changed in multiple stages until the calibrating function D(Z) is defined based on the results.

First, as schematically indicated by the five open circles on the graph **(A)** of FIG. **14(b)**, voltage command values **D** are selected in five stages. Then, drive voltages **V** are output in five stages in accordance with the characteristic

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function V(D) of the nonlinear D/A converter **176**.

Next, on the graph **(B)** shown in FIG. **14(b)**, as for the moving element **A1**, five displacements **Z** are plotted as indicated by the five open circles on the characteristic

5 function Z1(V) with respect to these drive voltages **V**. Likewise, as for the moving element **A2**, five displacements **Z** are plotted as indicated by the five open triangles on the characteristic function Z2(V). And the magnitudes of these displacements **Z** are sensed by the displacement sensing section

10 **170**.

Next, on the graph **(C)** shown in FIG. **14(b)**, the relationship between the displacement **Z** and the voltage command value **D** as detected by the displacement sensing section **170** is fitted with the calibrating function D(Z).

15 The nonlinear characteristics Z1(V) and Z2(V) of the moving elements are compensated for with the nonlinear characteristic V(D) of the nonlinear D/A converter **176**. That is why the calibrating functions D1(Z) and D2(Z) are substantially linear and the fitting operation can be carried

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out using a linear function as an approximation function. Accordingly, not just can the order of the approximation function be decreased but also isn't there any need to apply the approximation function to respective quadrants according to the signs of the voltage command value D and displacement Z. As a result, the approximation function can be handled synthetically over all quadrants and the fitting computations can be simplified significantly.

Also, if the linear function is used as an approximation function, then the voltage command value D can be directly represented as the function D(Z) of the displacement Z without decreasing the precision particularly significantly. This function notation D(Z) can be adapted more suitably to the converting section 173, which needs to convert the target displacement Z into the voltage command value D, than its inverse function notation Z(D). As a result, various conversion-related operations, including drawing up a conversion table, can be carried out more easily.

It is not always mathematically evident that both of

these calibrating functions D1(Z) and D2(Z) exhibit quasi-linear characteristics. One reason why these functions can be made linear with precision is that the characteristic functions Z1(V) and Z2(V) of the moving elements do not change

5   in arbitrary curves but with a certain tendency. More specifically, Z1(V) tends to be approximately equal to the product of Z2(V) and a predetermined constant. This is because the characteristic function Z(V) of the moving element changes mainly due to the variation in the spring constant of

10 the hinge 106 of the moving element. In this manner, in a system in which the hinge 106 of the moving element has linear restoring force and in which the magnitude of displacement is determined by the balance between the driving force and the restoring force, the nonlinear characteristic between the

15 driving force and the displacement is compensated for by providing non-linearity for the nonlinear D/A converter 176. Accordingly, the precision of linearity of the characteristic between the target displacement Z and the voltage command value D can be increased and the calibrating function D(Z) can

20 be calculated highly accurately through simple computations.

The microactuator of this preferred embodiment includes a nonlinear D/A converter **176** for converting a voltage command value **D** into a drive voltage **V** nonlinearly such that the greater the value of the drive voltage **V**, the smaller the

5   increase of the drive voltage **V** with the increase of the voltage command value **D**. Thus, the non-linearity of the characteristic between the drive voltage **V** and the displacement **Z** of the moving element can be compensated for and the relationship between the voltage command value **D** and

10 the displacement **Z** of the moving element can be made substantially linear. As a result, the number of bits of the voltage command value **D** to achieve required displacement resolution can be reduced and the overall circuit size and data transfer rate can be reduced as well.

15   In addition, the calibrating section **178** approximates the correlation between the voltage command value **D** and the displacement **Z** of the moving element with the calibrating function D(Z), which is a linear function. Thus, there is no need to apply the approximation function to respective

20 quadrants anymore according to the signs of the voltage

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command value **D** and displacement **Z**. As a result, the approximation function can be handled synthetically over all quadrants. On top of that, the voltage command value **D** can be directly represented as the function D(Z) of the displacement

5   **Z**. Consequently, the load of the calibrating computations can be reduced significantly.

As described above, according to the present invention, while a moving element is displaced in response to a drive signal supplied from the driving section, the displacement

10   sensing section senses the displacement and the calibrating section calibrates the correlation between the displacement and the drive signal. Thus, the displacement of each moving element can be sensed very easily without using any external displacement measuring device. And the variation in the

15   characteristic of the moving element either with time or according to the environment (such as the temperature) can be coped with.

In addition, the switching section selectively connects the driving section and/or the displacement sensing section to

one of the moving elements after another.   Accordingly, even

if the microactuator includes a plurality of moving elements,

the size of the displacement sensing circuit can be reduced

and the chip cost can be cut down.

5   .   Furthermore, by applying a microactuator with such a self

displacement sensing function to a deformable mirror, optical

control can be carried out with a simple configuration, with

sufficient   reliability   maintained   with   respect   to   the

variation with time or the environment, and with the loss of

10   light quantity minimized.

INDUSTRIAL APPLICABILITY

A microactuator according to the present invention is

applicable for use in not just deformable mirrors but also

15   various other types of equipment including radio frequency

circuits such as relay switches and tunable capacitors and

fluid-related devices such as micro-pumps.